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Exhaust of turbulence cloud at the tongue shaped deformation event

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Exhaust of turbulence cloud at the tongue-shaped deformation which triggers MHD bursts is observed in Large Helical Device (LHD) in the low density plasma with significant contribution of trapped particles injected by perpendicular neutral beam injection. The exhaust of turbulence cloud is characterized by the abrupt large increase of turbulence amplitude in the frequency range of 150 - 500 kHz measured with Doppler reflectometer at the edge region of the plasma ($r_{\rm eff}/a_{99}$=0.98). The increase of turbulence amplitude is significantly large and is by one order of magnitude. This abrupt increase of turbulence level is transient and disappears within one milli-second (typically $\sim 600\mu$s). In contrast, the turbulence level slightly inside the plasma edge ($r_{\rm eff}/a_{99}$=0.94) decreases by a factor of 2 after the MHD bursts.

PACS numbers:

I. INTRODUCTION

Coupling between the MHD instability and transport is one of the interesting topics in toroidal plasmas. The energetic particle driven MHD instabilities[1–4] can be violent enough to trigger the collapse of the plasma and have an impact on plasma turbulence and transport. The impact of the energetic particle driven MHD bursts on bulk plasmas has been studied in heliotron plasmas[5] and moderate decrease of density fluctuation during MHD burst are observed in LHD[6].

Recently, a tongue-shaped deformation[7, 8] was observed just before the MHD bursts and increase of density turbulence associated with the formation of the tongue shaped deformation was reported[9, 10]. The tongue shaped deformation observed in LHD has some similarity to the solitary perturbations (SPs) observed at Edge Localized Mode (ELM) in the KSTAR tokamak [11–13]. Both the tongue shaped deformation and solitary perturbations (SPs) are localized both poloidally and radially. They are detected within $\sim$100 μs before the collapse which is indicated by the sharp increases of D_α and RF intensity in ELM, and by the sharp increase of RF intensity in tongue shaped deformation. The change in the turbulence (especially turbulence frequency spectra) at the collapse has not been discussed, in spite of the importance of the physics mechanism on the coupling between the turbulence and MHD activity. The dynamics of the density fluctuation at the pedestal during the ELM cycles has been studied in DIII-D using beam emission spectroscopy (BES)[14]. The gradual increase of density fluctuation associated with the recovery of pedestal pressure gradient was identified. However, the time resolution of the BES measurements ($\sim$1 ms) is not good enough for discussing how the fluctuation changes at the collapse.

In this paper, the dynamics of the density fluctuation spectra measured with Doppler reflectometer at the collapse events are presented. The conditional averaging technique is used to investigate how the density fluctuation amplitude changes at the collapse event with the time resolution of 50 μs which is high enough to discuss the dynamics of turbulence at the collapse and the coupling between the turbulence and MHD instability.

II. DENSITY FLUCTUATIONS DURING THE TONGUE SHAPED DEFORMATION

The Large Helical Device (LHD) is a Heliotron-type device equipped with three tangential neutral beams with a beam energy of 160 - 180 keV and two perpendicular beams with a beam energy of 40 -50 keV. The frequency-hopping Doppler reflectometers have been installed in LHD and the frequency is set to 30 GHz in this experiment[15, 16]. The analysis technique of the radial scan of reflection point of the Doppler reflectometer using the density ramp up/down in time has been applied in LHD experiment. This method has been recognized to be a useful technique to measure the radial profile of density fluctuation amplitude and perpendicular velocity near the plasma edge[17].

When the two perpendicular beams are injected into the plasma with relatively low density of 1-2 $\times$ 10^{19}m^{-3}, the tongue shaped deformation and resulting MHD bursts appear associated with the enhancement of high frequency RF signals. Figure 1 shows time evolutions of electron density profile measured with YAG Thomson scattering system, reflection point of the doppler reflectometer, frequency spectra of density fluctuations measured with doppler reflectometer, fluctuation amplitude

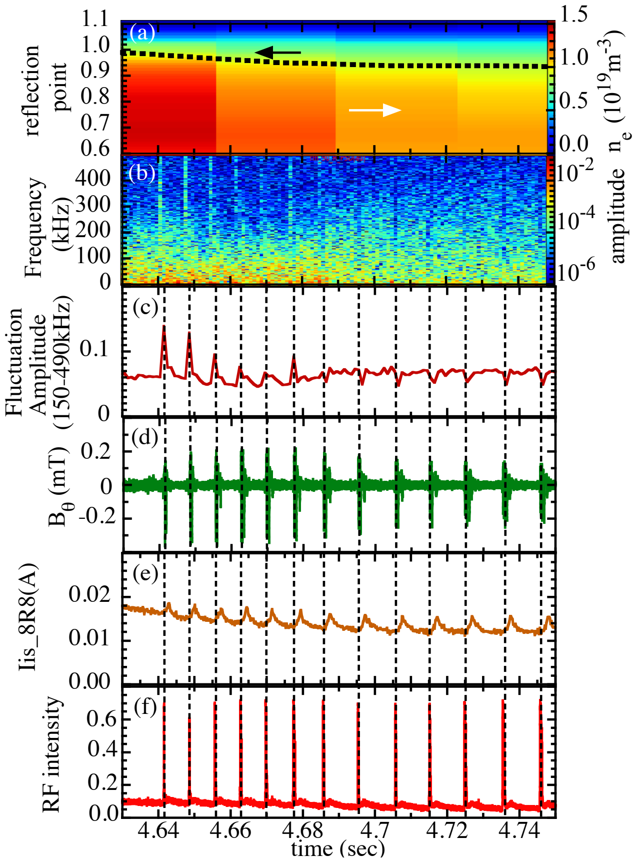

FIG. 1: Time evolution of (a) contour of smoothed electron density (right y-axis) and reflection point of the doppler reflectometer (left y-axis), (b) frequency spectra of density fluctuations measured with doppler reflectometer, (c) fluctuation amplitude in the frequency range of 150 - 490 kHz, (d) magnetic filed B_θ at toroidal angle of $\phi = 270°$, (e) ion saturation current at divertor probe (8R8), and (f) RF intensity at 880 MHz measured with RF radiation probe.

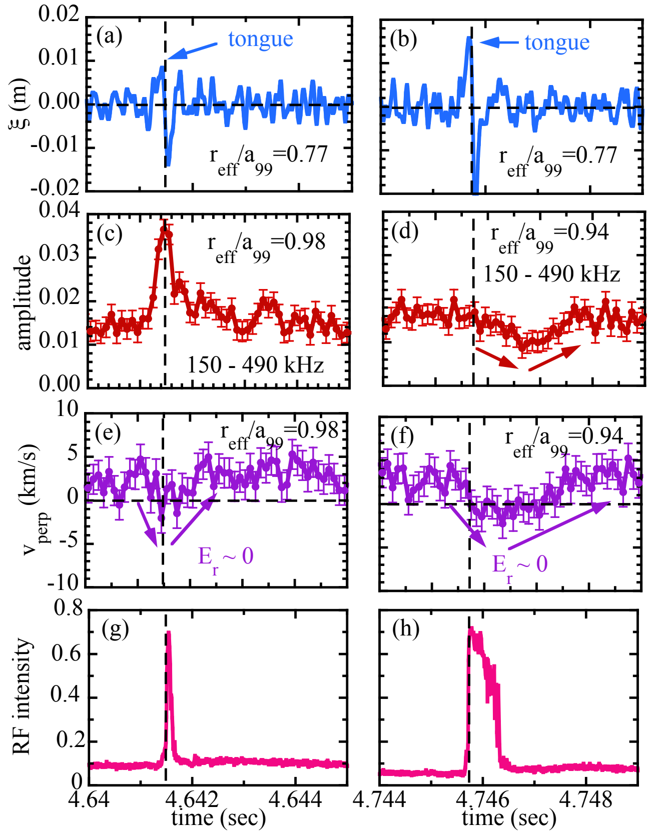

FIG. 2: Time evolution of (a)(b) displacement of displacement of the plasma at $r_{\rm eff}/a_{99} = 0.77$, (c)(d) density fluctuation amplitude in the frequency range of 150 - 490 kHz, (e)(f) perpendicular velocity, and (g)(h) RF intensity at 880 MHz measured with RF radiation probe during the collapse event at (a)(c)(e)(g) $t = 4.6415$ sec where the reflection point locates at $r_{\rm eff}/a_{99} = 0.98$ and at (b)(d)(f)(h) $t = 4.7457$ sec where the reflection point locates at $r_{\rm eff}/a_{99} = 0.94$.

in the frequency range of 150 - 490 kHz, magnetic field B_θ at toroidal angle of $\phi = 270°$, ion saturation current of one of the divertor probes, and RF intensity at 880 MHz measured with RF radiation probe at ($\phi = 121°$). The reflection point of the Doppler reflectometer (dotted line) is evaluated from the density profiles by interpolating (in time) the adjacent two smoothed (in space) density profiles measured with YAG Thomson scattering system every 33.3 ms. The RF radiation probes are widely used as a timing indicator for the energetic ion loss from the plasma[18, 19], because RF probe has high time resolution and high sensitivity to the instability excited by the loss of energetic ions at the plasma edge[20, 21].

In this discharge, the line averaged density electron density gradually decreases from 1.3 $\times$ 10^{19}m^{-3} to 1.1 $\times$ 10^{19}m^{-3} in time (from t = 4.63 to t = 4.75 sec) and the reflection point of the doppler reflectometer moves inward from $r_{\rm eff}/a_{99} = 0.98$ to $r_{\rm eff}/a_{99} = 0.94$. The MHD events characterized by the MHD bursts with 5 - 10 kHz oscillation in magnetic probe is triggered by the tongue shaped deformation inside the plasma[9]. These MHD events are also associated with the increase of ion saturation current of divertor probes and the jump of RF intensity, which indicates the bursty loss of bulk plasma and energetic ions. Although the repeated MHD events are almost identical during this time period (t = 4.63 - 4.75 sec), the behavior of density fluctuation amplitude is quite different between at the earlier events (t = 4.63 - 4.68 sec) and at the later events (t = 4.68 - 4.75 sec). The fluctuation amplitude increases at the earlier events, while it decreases at the later events. Therefore, the change in the density fluctuation behavior at each event is due to the inward movement of the reflection point of the Doppler reflectometer.

Figure 2 shows time evolution of displacement of the plasma evaluated from the time evolutions of electron temperature and its gradient measured with electron cyclotron emission (ECE) at $r_{\rm eff}/a_{99} = 0.77$, density fluctuation amplitude, perpendicular velocity, and RF intensity at 880 MHz measured with RF radiation probe during the collapse event at $r_{\rm eff}/a_{99} = 0.98$ and at $r_{\rm eff}/a_{99} = 0.94$. Here the displacement of the plasma is calculated from the high frequency (1 - 10 kHz) change in temperature and quasi-state temperature gradient (< 40 Hz) measured with ECE. The positive spikes of the displacement at $r_{\rm eff}/a_{99} = 0.77$ are the indication of tongue shaped deformation [9], while the negative spikes indicates the collapse of tongue [22]. In Figure 2, the error bars of the amplitude of density fluctuation and perpendicular velocity are evaluated from the standard deviation of these values in the steady state phase where they are expected to be constant in time. At the event in $t = 4.6415$ sec, when the reflection point of the Doppler reflectometer locates at the plasma edge ($r_{\rm eff}/a_{99} = 0.99$), the amplitude of density fluctuation increases associated with the formation of tongue (positive spike of plasma displacement) at a few hundred micro second before the sharp increase of RF intensity. This large increase of density fluctuation amplitude disappears associated with the tongue collapse (negative spike of plasma displacement). This transient increase of density fluctuation amplitude appears at the transient phase during the formation and collapse of the tongue shaped deformation. In contrast, the amplitude of density fluctuation shows moderate decrease after the collapse of tongue at the event in $t = 4.7457$ sec, when the reflection point of the Doppler reflectometer locates inside the plasma ($r_{\rm eff}/a_{99} = 0.94$). The change in perpendicular velocity measured with Doppler reflectometer shows that the positive radial electric field disappears ($E_r \sim 0$) after the tongue collapse. The disappearance of the positive electric field is due to the non-ambipolar ion loss associated with the tongue collapse.

III. CHANGE IN RADIAL STRUCTURE AND FREQUENCY SPECTRA OF DENSITY FLUCTUATIONS AT THE COLLAPSE EVENTS

Because the reflection point of the doppler reflectometer gradually moves inward, the radial structure of density fluctuation can be measured by accumulating the density fluctuation signal with respect to the event onset. Here the time of the sharp increase of RF signal is used as the reference of time ($\tau = 0$). This sharp increase of RF intensity is widely used as an indication of energetic ion loss associated with the MHD events[18].

Figure 3 shows the contour of density fluctuation amplitude in the low (3-30 kHz), middle (30-150 kHz) and high (150-490 kHz) frequency range with the time resolution of 50 μs for 2 ms before and after the collapse of energetic ion indicated by the sharp increase of RF intensity. The y-axis is the reflection point of the Doppler reflectometer at each MHD events. The reflection point moves inwards due to the gradual increase of electron

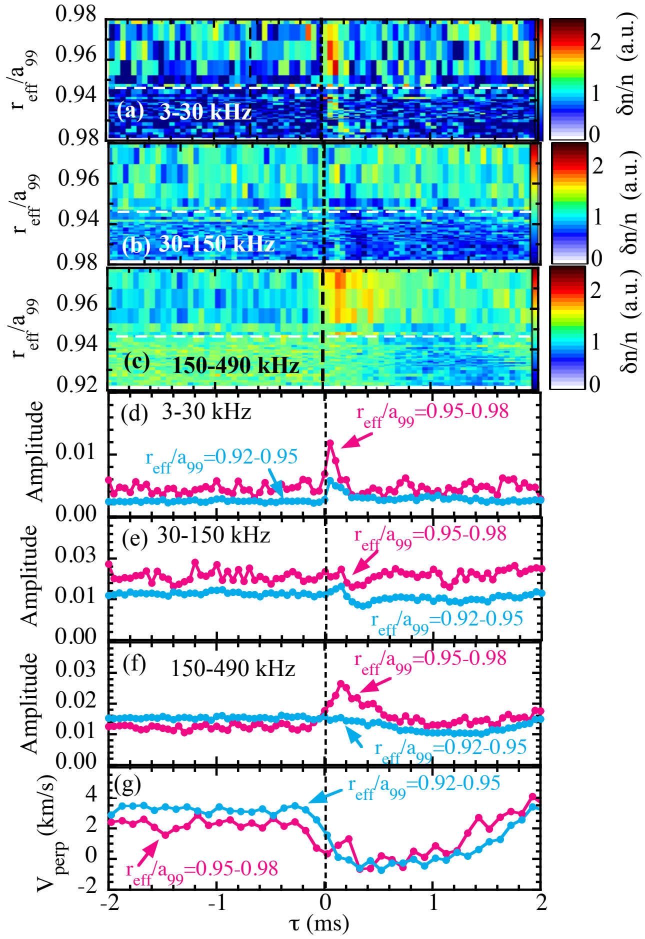

FIG. 3: Contour of density fluctuation in space and in time for (a) low (3 - 30 kHz), (b) middle (30 - 150 kHz), and (c) high (150 - 450 kHz) frequency range at the collapse event (τ = 0). Time evolution of integrated density fluctuation amplitude for (d) low (3 - 30 kHz), (e) middle (30 - 150 kHz), and (f) high (150 - 490 kHz) frequency range and (g) perpendicular velocity. The horizontal lines are the boundary between the edge region ($r_{\rm eff}/a_{99}$ = 0.95 -0.98) and inner region ($r_{\rm eff}/a_{99}$ = 0.92 - 0.95) of the plasma applied for the plot in Fig. (d)(e)(f)(g).

density during the repeated MHD bursts.

The increase of density fluctuation amplitude in the low (3-30 kHz) frequency is transient (∼200 μs) and is correlated to the MHD oscillation observed in the magnetic probe signal at the frequency of 5 - 10 kHz. Therefore, increase of density fluctuation amplitude in the low frequency is due to the direct effect of MHD oscillation. The increase is more significant at the plasma edge ($r_{\rm eff}/a_{99}$ = 0.95 - 0.98) where the fluctuation amplitude is larger. There is no increase of density fluctuation amplitude in the middle (30-150 kHz) frequency range observed at the plasma edge and a small decrease of the density fluctuation amplitude is observed slightly inside

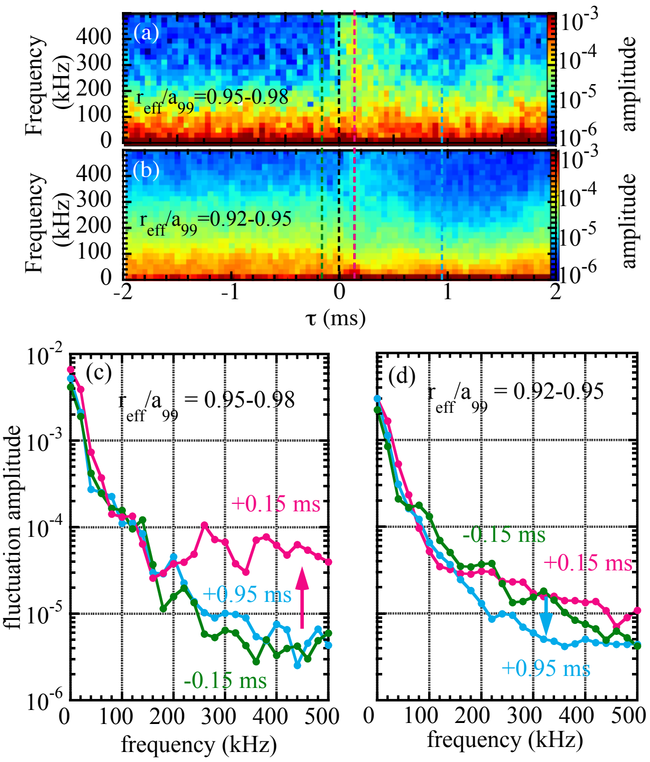

FIG. 4: Contour of density fluctuations amplitude in frequency and in time at the collapse event ($\tau = 0$) at (a) r_{eff}/a_{99} = 0.95 - 0.98 and at (b) r_{eff}/a_{99} = 0.92 - 0.95. Density fluctuations spectra 0.15 ms before and 0.15ms and 0.95ms after the collapse event at (c) r_{eff}/a_{99} = 0.95 - 0.98 and at (d) r_{eff}/a_{99} = 0.92 - 0.95. The vertical lines in Figs (a) and (b) indicate the timing of the time sliced spectrum plotted in Figs (c) and (d).

the plasma edge (r_{eff}/a_{99} = 0.92 - 0.95). In contrast, in the high frequency density fluctuation (150 - 490 kHz), a significant increase is observed at the plasma edge while a small decrease is observed slightly inside the plasma edge. The increase of high frequency density fluctuation (150 - 490 kHz) is also transient ($\sim$600 μs) but longer than that in the low frequency. The rapid increase of high frequency density fluctuation is considered to be an exhaust of turbulence cloud, because the time evolution of the perpendicular velocity, which has a strong impact on turbulence suppression/enhancement, is almost identical between the edge region (r_{eff}/a_{99} = 0.95 - 0.98) and the inner region (r_{eff}/a_{99} = 0.92 - 0.95).

In order to improve the signal to noise ratio, the conditional averaging with respect to the time of RF sharp increase is applied to the frequency spectra analysis of the density fluctuation for the edge region (r_{eff}/a_{99} = 0.95 - 0.98) and the inner region (r_{eff}/a_{99} = 0.92 - 0.95), respectively. Figure 4 shows the change in frequency spectra of density fluctuations during the MHD events (from 2ms before to 2ms after the collapse of energetic ion indicated by the sharp increase of RF intensity) with the time resolution of 50 μs at the edge r_{eff}/a_{99} = 0.95 - 0.98 and at the inner region r_{eff}/a_{99} = 0.92 - 0.95 of the plasma. Significant change of density fluctuation spectra at the plasma edge (r_{eff}/a_{99} = 0.95 - 0.98) is observed at the tongue collapse. The increase of density fluctuation by one order of magnitude is observed in the frequency range of > 150 kHz. Only the high frequency turbulence increases, while the lower frequency density fluctuation is unchanged. The change in density fluctuation inner region (r_{eff}/a_{99} = 0.92 - 0.95) shows different behavior. The density fluctuation in the frequency range of 150 - 450 kHz decreases moderately after the MHD events. The decrease of the fluctuation amplitude is by a factor of two, which is much smaller than the order of magnitude increase of the fluctuation amplitude at the plasma edge. This moderate decrease of density fluctuation amplitude in the inner region of the plasma is also observed in the density fluctuation amplitude measured with phase contrast imaging (PCI) diagnostic in LHD[6].

IV. DISCUSSION AND SUMMARY

The rapid change in spectrum of density fluctuation is observed at the MHD event triggered by the tongue shaped deformation. There are two important findings in this experiment. One is rapid large increase of density fluctuation at the plasma edge at the MHD event and the other is slow small decrease of density fluctuation in the inner region of the plasma after the MHD event. The increase of density fluctuation is transient ($\sim$200 μs) in the low MHD frequency and $\sim$600 μs in the high turbulence frequency (f = 150 - 490 kHz). The increase of density fluctuation is clearly observed at the plasma edge (r_{eff}/a_{99} = 0.95 - 0.98) but is not observed in the inner region of the plasma (r_{eff}/a_{99} = 0.92 - 0.95).

The possible mechanism causing the exhaust of turbulence cloud at the event of tongue shaped deformation is large poloidal electric field which could cause the $E_\theta \times B$ motion of the turbulence clouds as well as plasma. If we assume the plasma motion of the tongue plotted in figure 2 is due to the $E_\theta \times B$, the magnitude of the poloidal electric field is evaluated as $E_\theta \sim$ 300 V/m [9]. This large poloidal electric field would be a result of nonlinear stages of $E_\theta \times B$ shear and/or ∇T_e instabilities [23]. Both the tongue shaped deformation (outward displacement of the plasma) and increase of high frequency density fluctuation start to increase $\sim$100 μs before the energetic ion loss indicated by the sharp increase of RF intensity. This observation is consistent with this hypothesis.

The transient increase of turbulence amplitude identified in this experiment differs from the blob observed in LHD[24–26]. The blob is characterized by the very sharp positive spikes observed in the ion saturation current. The time scale of the blob in LHD is typically from 5 to a few tens of μs, which is much shorter than the transient increase of turbulence amplitude at the tongue events. The time scale of increase of ion saturation current at the event is 2 - 3 ms. The increase is only 10 - 20% and there are no sharp spikes observed. The sharp increase of density fluctuation is the outward propagation of the turbulence clouds by the $E_\theta \times B$, while the blob is the propagation of plasma cloud by $E_{\rm blob} \times B$, where $E_{\rm blob}$ is the internal electric field in the blob.

In conclusion, the simultaneous increase/decrease of density fluctuation in the frequency region of turbulence at the edge and inner region of the plasma the plasma is a clear evidence of exhaust of turbulence clouds near the plasma edge, associated with the tongue-shaped plasma deformation and collapse. The increase of density fluctuation at the formation and collapse of tongue shaped deformation is transient ($\sim 600\mu$s) and is significantly large (by one order of magnitude), while the decrease of density fluctuation after the tongue collapse is moderate (by a factor of 2).

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